THE FORCED UPPER OCEAN DYNAMICS EXPERIMENT IN THE ARABIAN SEA: RESULTS FROM THE MULTI-VARIABLE MOORED SENSORS FROM DEPLOYMENT-2 OF THE WHOI MOORING

by C. Ho, C.S. Kinkade, C. Langdon, M. Maccio, J. Marra

LDEO TECHNICAL REPORT
LDEO-96-8

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Lamont-Doherty Earth Observatory
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1. GUIDE TO FIGURES WITH CAPTIONS

2. INTRODUCTION

Multi-variable moored systems (MVMS) (Dickey *et al.*, 1991) were used to collect physical and bio-optical data over a 1-year period in the Arabian Sea as part of the ONR sponsored program, "Forced Upper Ocean Dynamics." The MVMS consists of a fluorometer, a thermistor, a conductivity sensor, a photosynthetic available radiation (PAR) sensor, a beam transmissometer, a 683nm upward vertical radiation sensor (Lu683), a dissolved oxygen sensor with a temperature sensor, and a vector measuring current meter (VMCM).

The mooring was deployed south off the Arabian Peninsula at 15°30.04' N and 61°29.99' E (Fig.1), from April 22 (day 112), 1995 to October 20 (day 293), 1995. The overall mooring is shown in Fig. 2. The subsurface moored array included four MVMS. This report discusses data collected by two MVMS (at 10 m and 65 m), prepared by LDEO. Two others were deployed at 35 m and 80 m by the Ocean Physics Group at the University of Southern California. For data on the VMCM's temperature sensors, and data from the meteorological buoy at the surface, see Trask et al. (1995).

The mooring was centrally located among an array of four other subsurface moorings. Two to the west were deployed by Dan Rudnick and two to the east were deployed by Charlie Eriksen. Thus the mooring site was an array of five moorings, centered on the one which held the MVMS'.

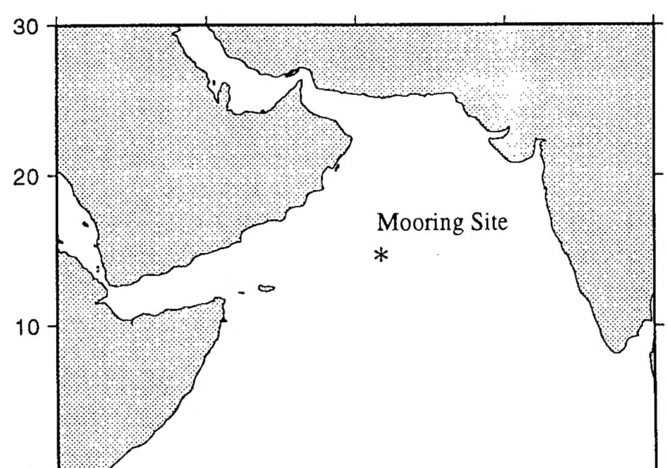

Fig. 1 The geographic location of the mooring

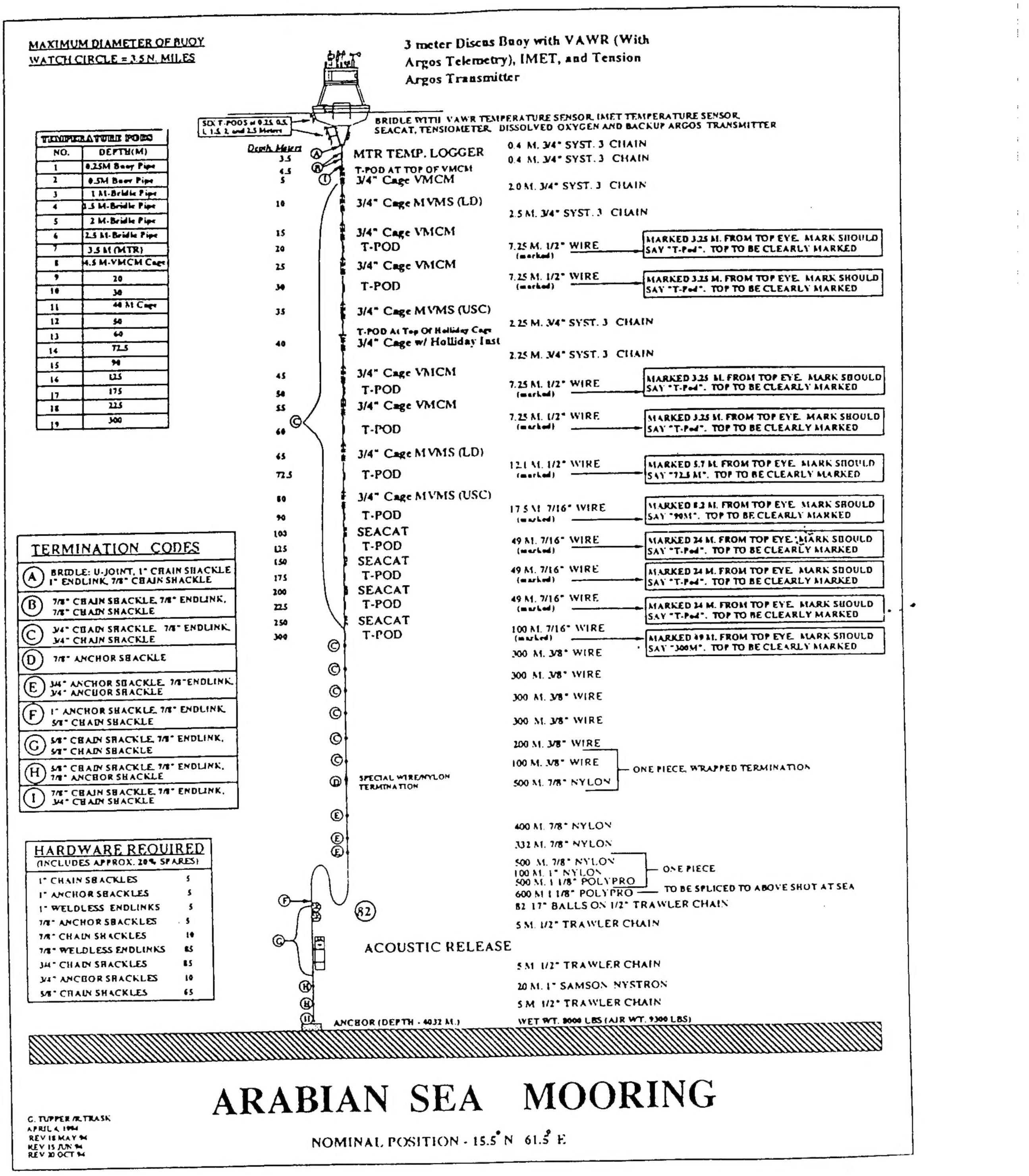

Fig.2 The mooring diagram

(The mooring was built at WHOI under the direction of R. Weller)

2.1 Record Format

All signals from sensors are processed by a Tattletale Model 6 computer and results were stored in a hard disk as ASCII files. Records are put into files every 256 second. Each record contains 15 fields: Sample number, Wake up signal, time, date, FLuorometer, TEmperature, COnductivity, PaR, TRansmissometer, Lu683, Voltage, electrical current(I), Dissolved Oxygen, dissolved oxygen temperature, and VMCM readings. A typical record is shown below:

```
S 00023101 W 00085158 06:58:39 12/09/94
FL 0093 TE 35810 CO 10230 PR 0161 TR 4599 683 0000 V 1336 I 0340

DO 1851 08E7
VM
F02F53456FF9DF307FCF4F9888F505A3C005D8B3B27CE00D311F90000538181A0
934E0
```

Except for the date, time and VMCM readings, all numbers are in decimal format.

3. SENSOR CALIBRATION CONSTANTS

3.1 Stimulated Fluorescence

Voltage from the fluorometer (Sea Tech, Corvallis, OR) was recorded at the fifth field. Calibration of all the fluorometers was done according to Marra and Langdon (1993). The formula used was:

$$\text{Chlorophyll } (\mu g\ l^{-1}) = m_{chl} \cdot FLU + b_{chl}$$

where FLU is the value in volts.

Table 1 shows the values of the constants in the equation.(See Appendix A for details.)

Table 1: Fluorometer Calibration Coefficients

depth	SN#	m_{chl}	b_{chl}
10	131	0.8808	-0.108
65	6	0.8808	-0.108

3.2 Temperature

There are three thermistors on each MVMS. The first one is part of the VMCM. It will be discussed in the section for VMCM data. The second sensor was a Sea-Bird thermistor (SBE-3). Data were recorded in the sixth field of each data record. This temperature was calculated using the formulas:

$$R = A0 / TEM$$

$$\text{Temperature}(^\circ C) = 1/(AT + BT \cdot \ln(R) + CT \cdot (\ln(R))^2 + DT \cdot (\ln(R))^3) - 273.15$$

Temperature calibration coefficients, from a calibration by SBE, are in Table 2.

The third thermistor was part of the Endeco (Marion, MA) oxygen sensor. The data were recorded as the second number after the symbol 'DO'.

The formula used for calibration were:

$$R = A0 + A1 \cdot TEM$$

$$\text{Temperature}(^\circ C) = 1/(AT + BT \cdot \ln(R) + CT \cdot (\ln(R))^3) - 273.15$$

The calibration coefficients are listed in Table 3.

Table 2: SBE Thermistor Calibration Coefficients

depth	SN	A0	AT x 10^3	BT x 10^4	CT x 10^5	DT x 10^6
10m	1749	5373.34	3.68034	5.87439	1.41752	2.22848
65m	1748	5474.90	3.68034	5.85039	1.39979	2.34426

Table 3: Endeco Thermistor Calibration Coefficients

depth	SN #	A0	A1	ATx10^3	BTx10^4	CTx10^8
10m	50	8140.6	-0.8134	1.42399	2.46280	6.53783
65m	49	8123.1	-0.8115	1.37327	2.55369	1.65966

3.3 Conductivity

The conductivity sensors were model SBE-4, and calibrated by SBE prior to deployment. Conductivity, the seventh field of the data record, was calculated using the Sea-Bird formula

$$\text{Conductivity(mmho/cm)} = a \cdot CON^m + b \cdot CON^2 + c + d \cdot t$$

where b, c, d and m are calibration constants for each sensor, and t, temperature in °C.

Constants for conductivity calculation:

Table 4: Calibration Coefficients for SBE-4 Conductivity Sensors

depth	SN #	a x 10^7	b x 10	c	d x 10^5	[illegible]
10m	1508	58.398	5.62783	-4.2223	16.467	4.6
65m	1506	41.877	5.3110	-4.06956	-15.691	4.7

Conductivity was then converted to salinity by formulas from UNESCO/ICES/SCOR/IAPSO (1981).

3.4 Photosynthetically Available Radiation (PAR) (Scalar Irradiance), and 683nm Upward Vertical Radiance (Lu683)

PAR sensors are QSP-200 from Biospherical Instruments (San Diego, CA). Vpar was recorded as decimal numbers, in the eighth field. The PAR in $\mu E/m^2/s$ was calculated from:

$$PAR = C / B \cdot (A + Vpar)$$

where C = calibration constant supplied by the manufacturer
B = gain from the signal processing board
A = offset from the signal processing board

Table 5: Calibration coefficients for QSL-200 PAR Sensors

depth	SN	A	B	C
10m	4236	0.0	1	353.644
65m	4289	0.0	12	302.175

Lu683 sensors (model QMR-200) are also from Biospherical Instruments. V683 was recorded in decimal numbers, the tenth field. Lu683 in $\mu E/m^2/s/nm/str$ was calculated from:

$$Lu683 = C / B \cdot (A + V683).$$

where C = calibration constant supplied by the manufacturer
B = gain from the signal processing board
A = offset from the signal processing board

Table 6: Calibration coefficients for QSL-200 Lu683 Sensors

depth	SN	A x 10^4	B	C x 10^2
10m	7016	-2.0	50	1.3984
65m	7014	-2.0	50	1.4669

3.5 Transmissometer

Sea Tech 25-cm pathlength transmissometers were used. The wavelength used by these sensors is 660 nm. The sensor output voltages, TRAN, were recorded in decimal numbers, in the ninth field. The conversion from voltage to %transmittance was:

$$X\% = 20 \cdot ((A / B) \cdot (TRAN - Z)$$

where A = air calibration voltage supplied by the manufacturer
B = present air calibration voltage

The coefficients used were in table 7.

Beam attenuation coefficient was calculated by:

$$b.a.c. = - \ln(X\%/100) / 0.25 - (b.a.c)_{clear\ water}$$

where $(b.a.c.)_{clear\ water} = 0.2757$, which was the average b.a.c. of deep water at the mooring site based on CTD data.

Table 7: Calibration Coefficients for Sea Tech Transmissometer

depth	SN#	A	B	Z
10m	299	4.798	4.534	0.00
65m	380	4.826	4.445	0.00

3.6 Dissolved Oxygen

Type 1133 Dissolved Oxygen Sensor was supplied by Endeco (Marion, MA). Calibration was performed by C. Langdon. Sensor output voltage, V_{O2}, the twelfth field, was converted to physical units using following procedures. The first step was to convert voltage (V_{O2}) to current units:

$$DOX = CA+CB \cdot V_{O2}$$

The DO concentration (O_2) in µmol/l was calculated as:

$$O_2 = Ss(T,S) \cdot [(DOX/OA+OB \cdot T)]$$

where Ss is the solubility coefficient with units µM/kPa, dependent on VMCM temperature (T, °C) and average salinity (S, in psu). Ss is given by equation:

$$Ss = Cstar/(0.20946 \cdot (101.325-pH_2O))$$

where

$$TK = T + 273.15$$

$$Cstar = \exp(A1+A2/TK+A3/TK^2+A4/TK^3+A\%/TK^4+S[A6+A7/TK+A8/TK^2])$$

$$pH_2O = \exp((-216961/TK-3840.7)/TK+16.4754$$

with
$A1 = 1135.90205$
$A2 = 15750.1$
$A3 = -6.642308*10^7$
$A4 = 1.2438*10^{10}$
$A5 = -8.621949*10^{11}$
$A6 = 0.017674$
$A7 = -10.764$
$A8 = 2140.7$

and the values of the CA, CB, OA, OB listed in Table 8. The TK and pH_2O equations come from Benson and Krause (1984) and Gnaiger and Forsther (1983).

Table 8: Dissolved Oxygen Calibration coefficients

depth	SN	CA	CB	OA	OB
10m	7	0.0	0.01097	2.799	0.032
65m	18	15.21	0.01047	3.249	0.0258

3.7 VMCM data

VMCM data are the last part of the record. It contains information on record count, north vector, east vector, rotor-2 counts, rotor-1 counts, compass value, and temperature. All data are recorded in hexadecimal. Each item is 4 characters long, except the compass value, which is 2 characters long.

3.7.1 Current Vectors

East and north current vector components, VE and VN, in engineering units (cm/s) were obtained from:

```
VE = K · VecE / t
VN = K · VecN / t
```

where K = 9.363 cm/count, VecE is the east vector count, VecN is the north vector count, and t is the averaging time interval in seconds. To account for magnetic declination, currents were rotated -19.5° (i.e. 19.5° west) using following formula:

```
new_VN = VN · cos(19.5) - VE · sin(19.5)
new_VE = VE · cos(19.5) + VN · sin(19.5)
```

3.7.2 VMCM temperature

In deployment-1, VMCM temperatures were the same as the Sea-Bird temperatures. For deployment-2, Sea-Bird temperatures were verified to be accurate by CTD temperatures. Thus, we have not independently calibrated the VMCM thermistor.

4. REMARKS ON THE DATA

4.1 Data validation

Temperature, salinity, b.a.c., and chlorophyll data were checked against other independently collected data. During the time of April 1995 and October 1995, R/V T.G. Thompson passed by the mooring site several times and data were collected in the vicinity. Following is the list of these cruises and stations.

Cruises	sta	cast	latitude	longitude	date	time	type
TN046	05	01	15°27.20'N	61°29.53'E	Apr 18,'95	18:00	BOTTLE
TN046	18	01	15°28.78'N	61°28.78'E	Apr 19,'95	15:26	BOTTLE
TN046	19	01	15°33.60'N	61°28.20'E	Apr 22,'95	13:31	BOTTLE
TN048	17	01	15°30.70'N	61°28.00'E	Jul 06,'95	01:36	CTD
TN049	24	01	15°31.80'N	61°30.10'E	Aug 05,'95	07:14	CTD
TN050	21	09	15°55.14'N	61°55.83'E	Sep 05,'95	08:47	CTD

If the data did not agree with these measurement, they were flagged with a number -9999.

4.2 Temperature

In deployment-1, thermistors were most accurate and stable of all the sensors. In deployment-2, again, they measured the temperature from beginning to end in a perfect match with independent measurements.

4.3 Salinity

Conductivity sensor at 10 m, became unstable around August 5, 1995 (day 217) and the data drifted away from the CTD conductivity. Data after that day were considered unreliable and were flagged with -9999.

The conductivity sensor at 65 m suffered some unstable problems before July 28, 1995 (day 209). The recorded signals were very low comparing to CTD measurements. These data were flagged with -9999.

4.4 PAR and Lu683

Both PAR sensors functioned well until the sensor diffuser became damaged by fish bite. For 10m, it happened on August 30, 1995 (day 240). For 65m, it was October 7, 1995 (day 280).

Both Lu683 sensors behaved well for the most part. At 10 m, the sensor had an amplifier gain problem. After July 9, 1995 (day 190), when Lu683 signal was strong around noon time, the signal was amplified too much causing an overflow. At 65m, after October 2, 1995 (day275), data were unreasonable. However, between July 28, 1995 (day 209) and October 2, 1995 (day 275), the signal was very low. All other data were properly recorded.

4.5 Beam attenuation coefficient

The glass windows of transmissometers at both 10 m and 65 m were found covered by gooseneck barnacles and filamentous algae at recovery. But the exact time the window started to show effects of fouling was not known.

At 10 m, judging by the b.a.c. ~ chlorophyll relation, data after June 9, 1995 (day 160) (see Appendix A) were considered unreliable. These data were flagged -9999.

At 65 m, data after May 15, 1995 (day 135) were considered to be unreliable (see Appendix A).

4.6 Chlorophyll

Fouling of the fluorometers was more severe during deployment-2 than deployment-1. In the early stage of fouling, the signal started to show many spikes. The frequency of spikes increased until all data consisted of spikes. A computer program was written to remove the spikes and replace them with previous values. Since, by replacing data, the original data become altered, this procedure should be stopped before too many data points were changed. For 10m, this date was determined to be July 19, 1995 (day 200). For 65m, de-spiking stopped on September 17, 1995 (day 260) (see Appendix A).

The pre-cruise calibration of both instruments was questionable. Appendix A discusses in detail how chlorophyll data were calibrated and verified. Basically, for 10 m, data after July 6, 1995 (day 187) were not reliable and flagged -9999 and for 65 m, data before September 17, 1995 (day 260) were reliable.

4.7 Dissolved Oxygen

At 10 m, the sensor became unstable after June 10,1995 (day 161). Data after this date have been flagged -9999. At 65 m the sensor failed on October 6, 1995 (day 279). Data after this date have been flagged -9999. At the beginning of the deployment, there was a large discrepancy between CTD value and mooring value (Fig. 6). However both measurements were considered inaccurate. These numbers are presented as reference only.

4.8 Current Vectors

As part of the project "Forced Upper Ocean Dynamics", Weller of Woods Hole Oceanographic Institution also measured current speed as a function of depth. Our data are compared with the WHOI data in Fig. B1. In this figure, 10m and 65m data during the period between April, 1995 and October, 1995 were the same data set as in this report. The flow patterns we observed 10 and 65m are comparable with other depths.

5. REFERENCES

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Benson, B. and D. Krause.1984. The concentration and isotopic fractionationof oxygen dissolved in freshwater and seawater in equilibrium with the atmosphere. Limnol. Oceanogr. 29, 620-632

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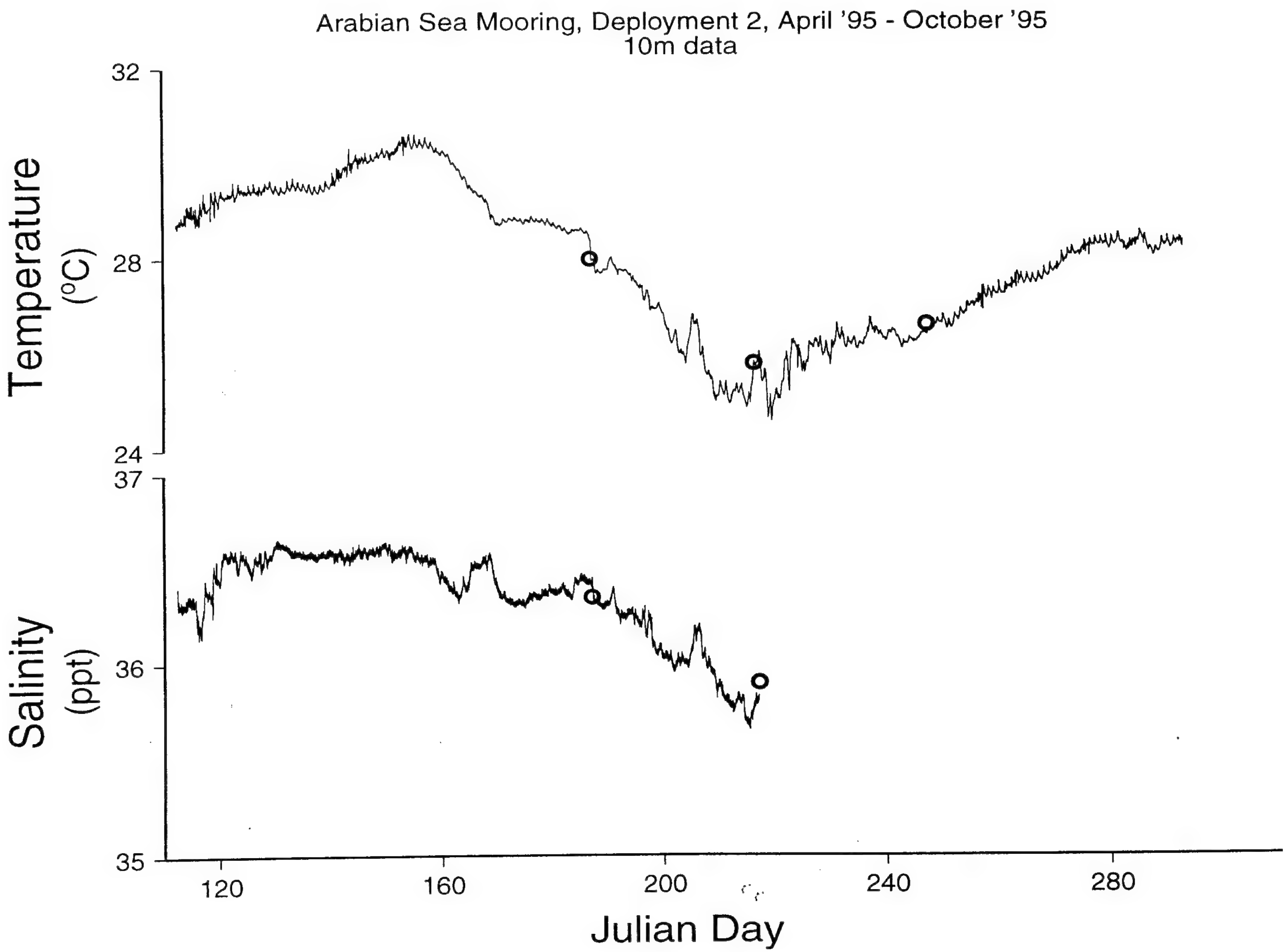
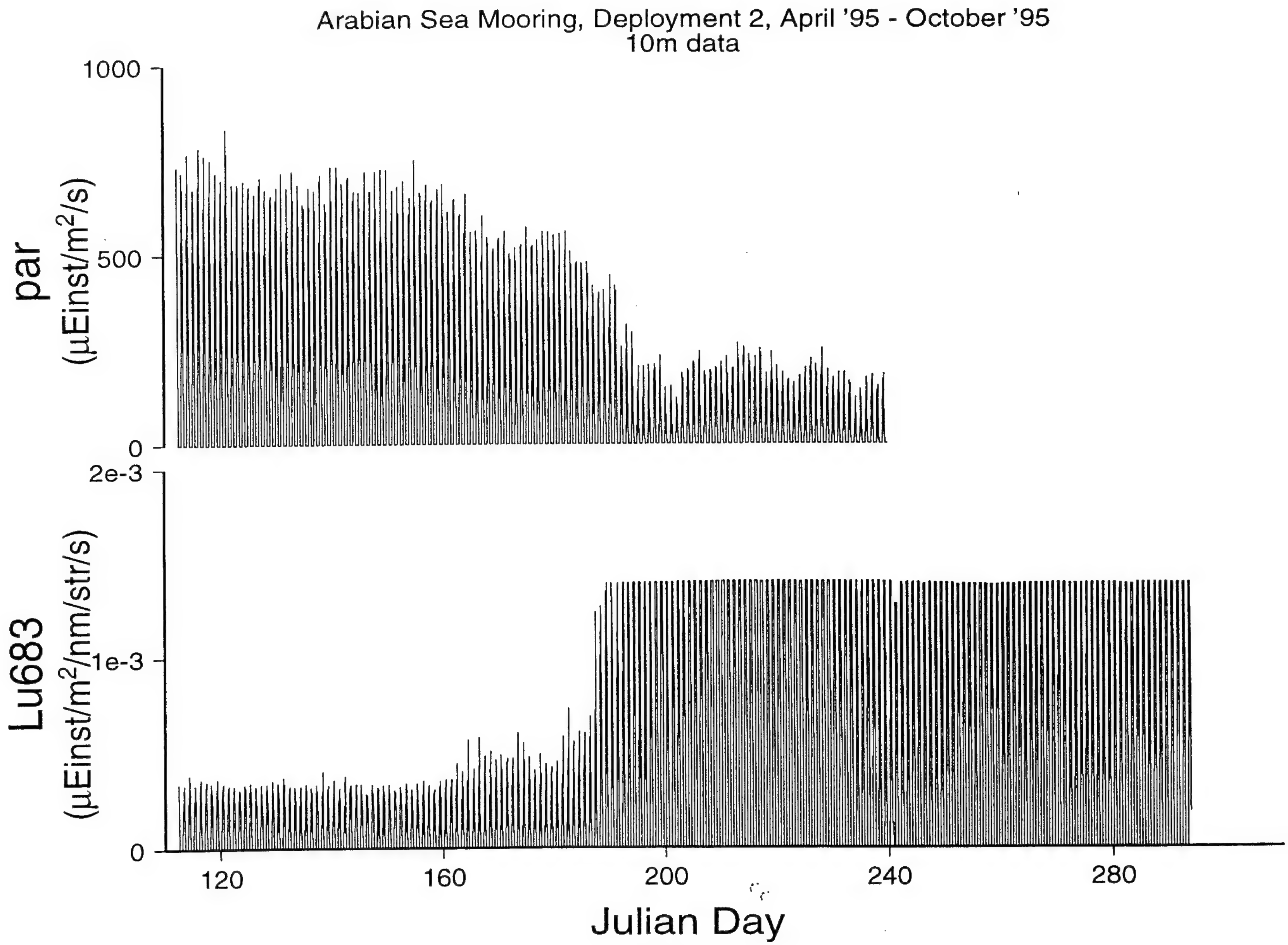

Arabian Sea Mooring, Deployment 2, April '95 - October '95
10m data
Temperature
(°C)
32
28
24
Salinity
(ppt)
37
36
35
120
160
200
240
280
Julian Day
Fig.3



Arabian Sea Mooring, Deployment 2, April '95 - October '95
10m data
par
(µEinst/m²/s)
1000
500
0
Lu683
(µEinst/m²/nm/str/s)
2e-3
1e-3
0
120
160
200
240
280
Julian Day

Fig.4

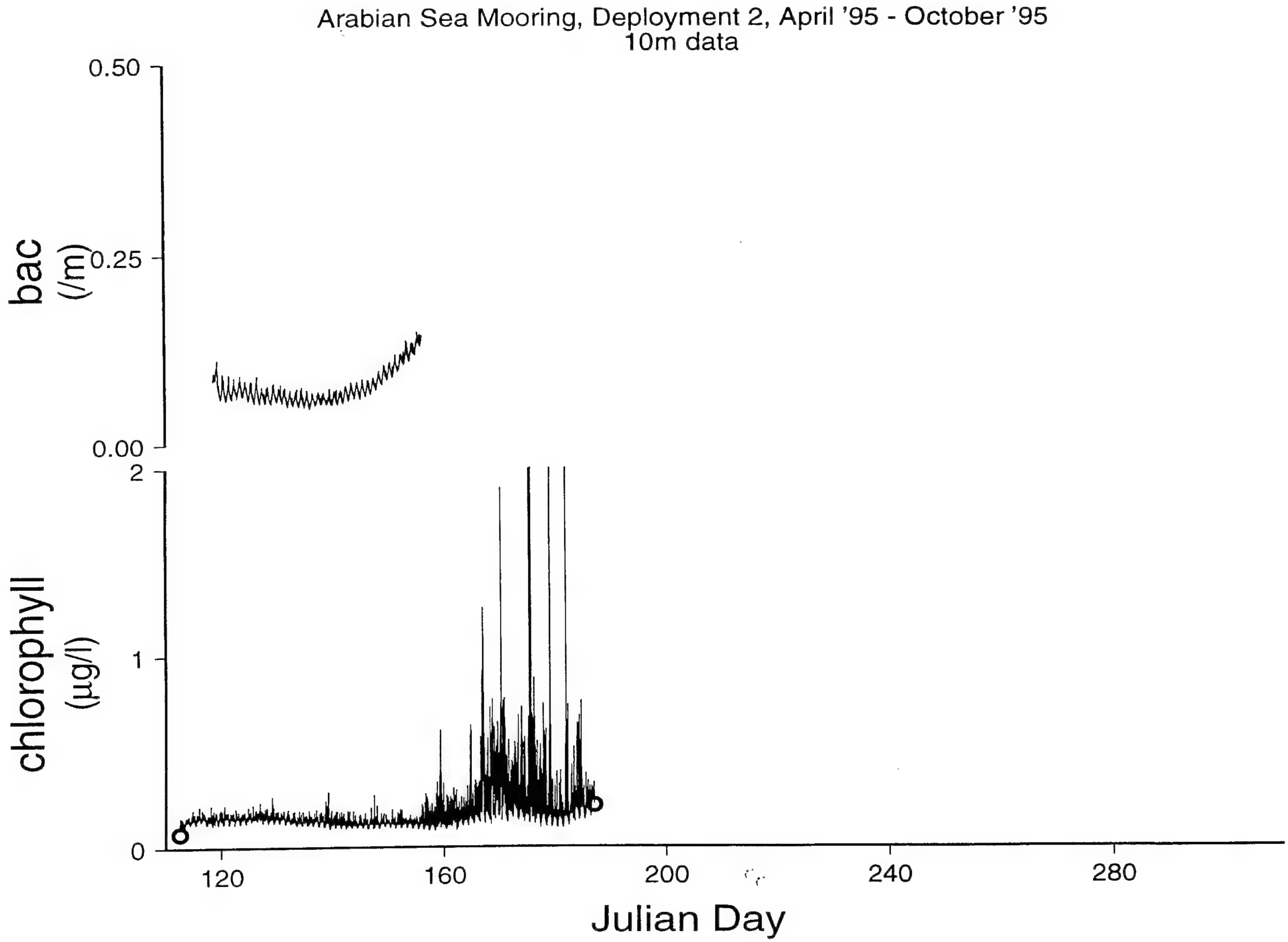
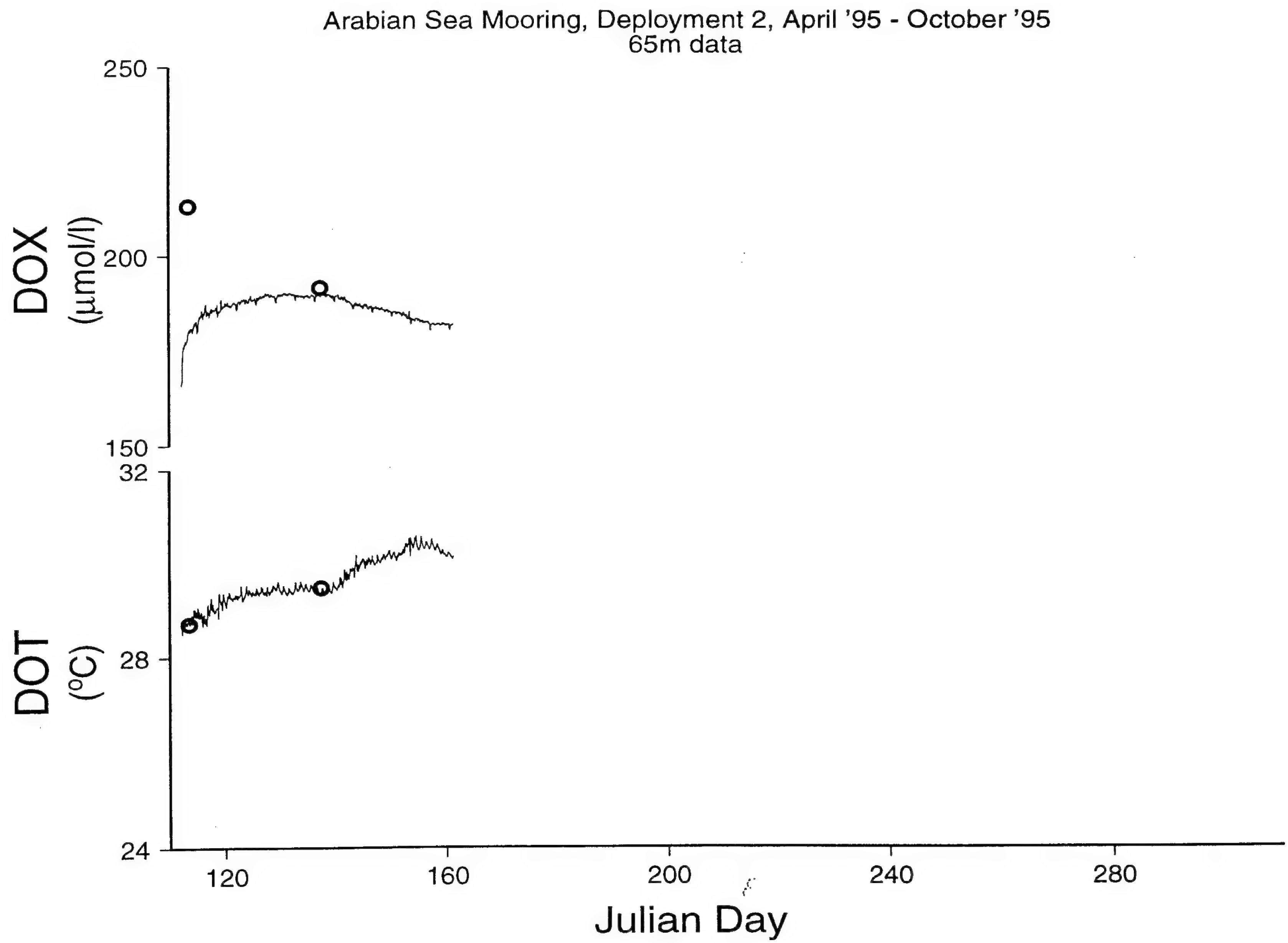
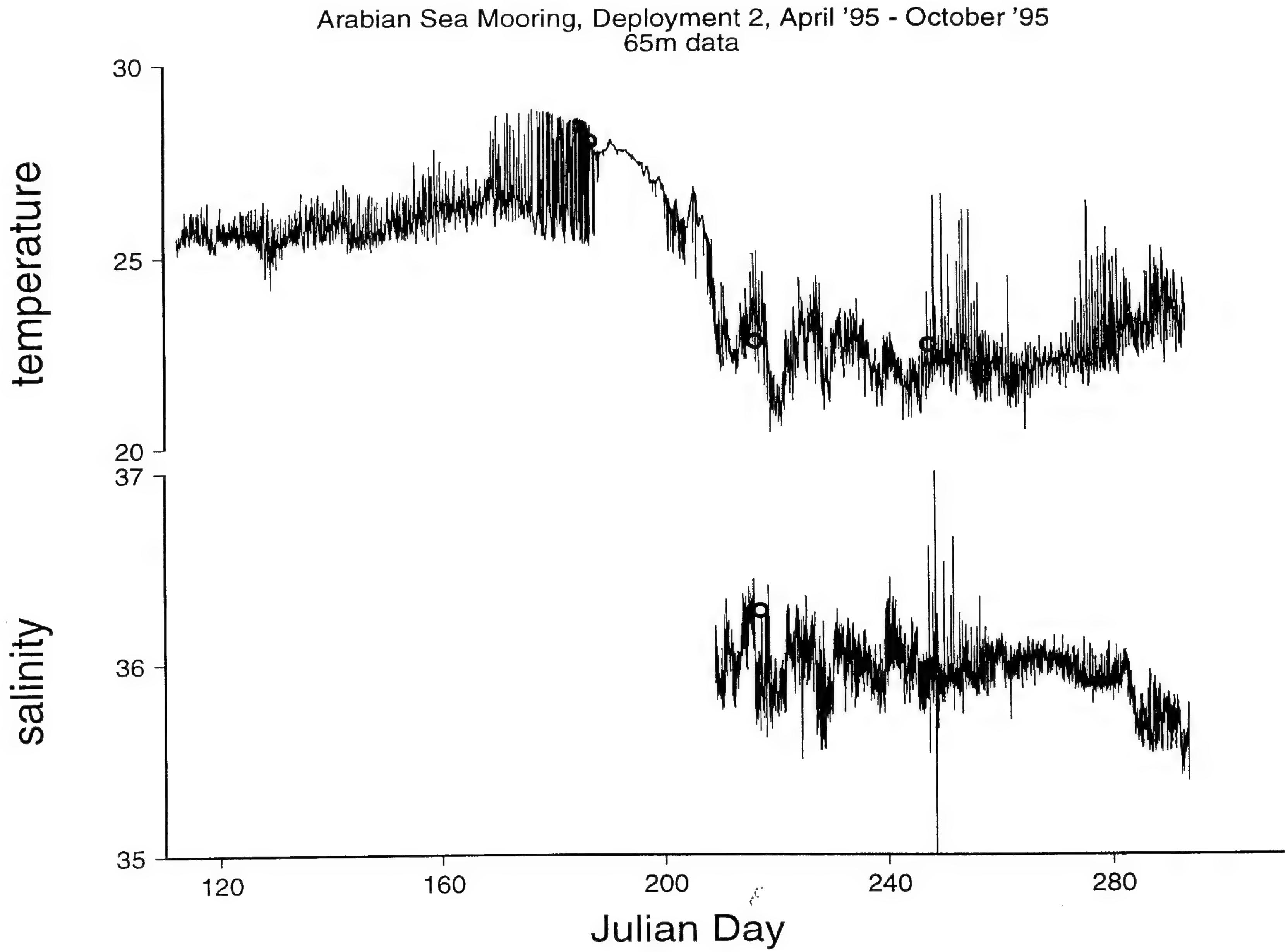

Arabian Sea Mooring, Deployment 2, April '95 - October '95
10m data
bac
(/m)
0.50
0.25
0.00
chlorophyll
(µg/l)
2
1
0
120
160
200
240
280
Julian Day

Fig.5



Arabian Sea Mooring, Deployment 2, April '95 - October '95
65m data
DOX
(μmol/l)
250
200
150
DOT
(°C)
32
28
24
120
160
200
240
280
Julian Day

Fig.6


Arabian Sea Mooring, Deployment 2, April '95 - October '95
65m data
30
25
20
37
36
35
temperature
salinity
120
160
200
240
280
Julian Day
Fig.7

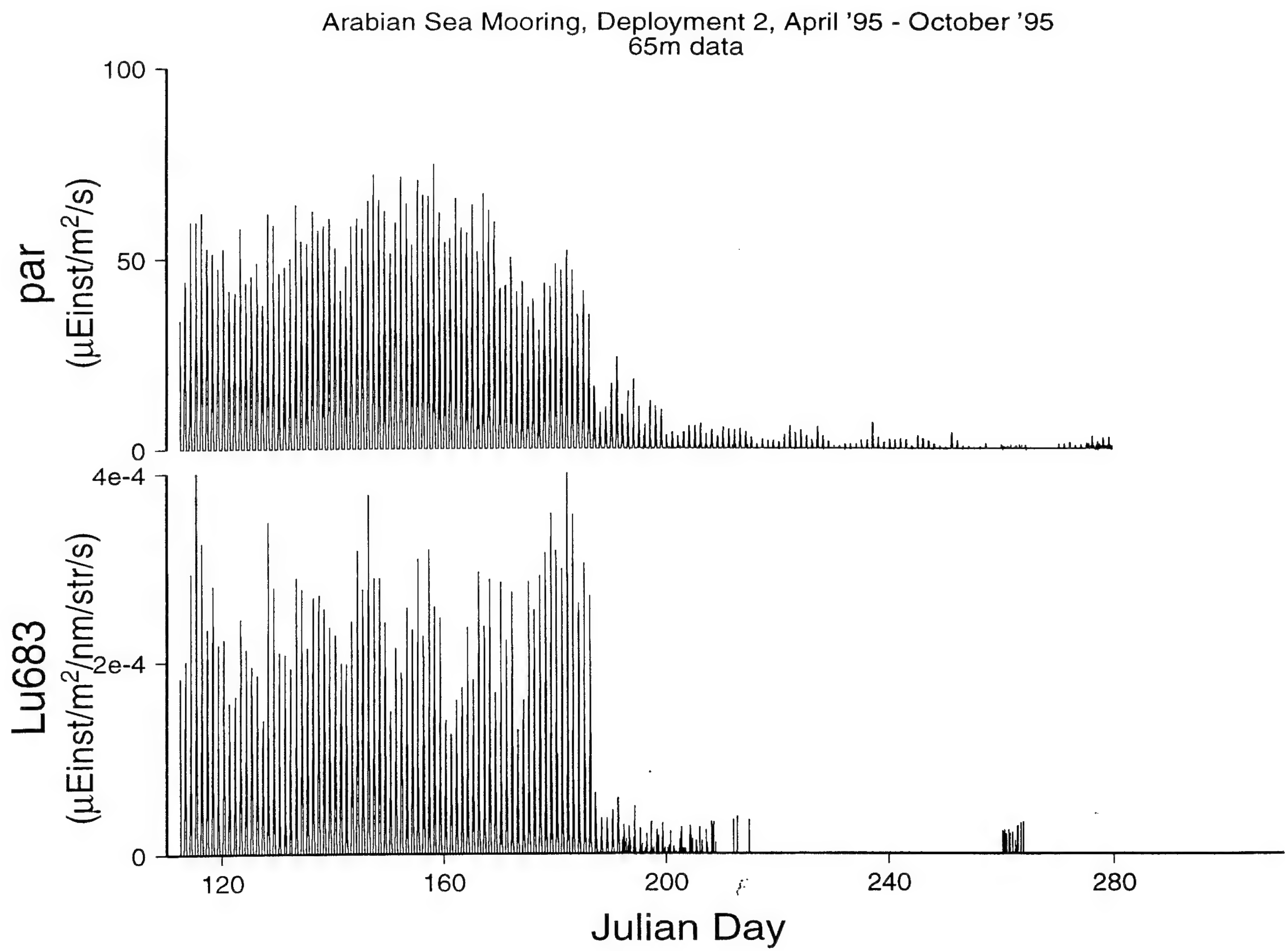

Arabian Sea Mooring, Deployment 2, April '95 - October '95
65m data
par
(µEinst/m²/s)
100
50
0
Lu683
(µEinst/m²/nm/str/s)
4e-4
2e-4
0
120
160
200
240
280
Julian Day

Fig.8

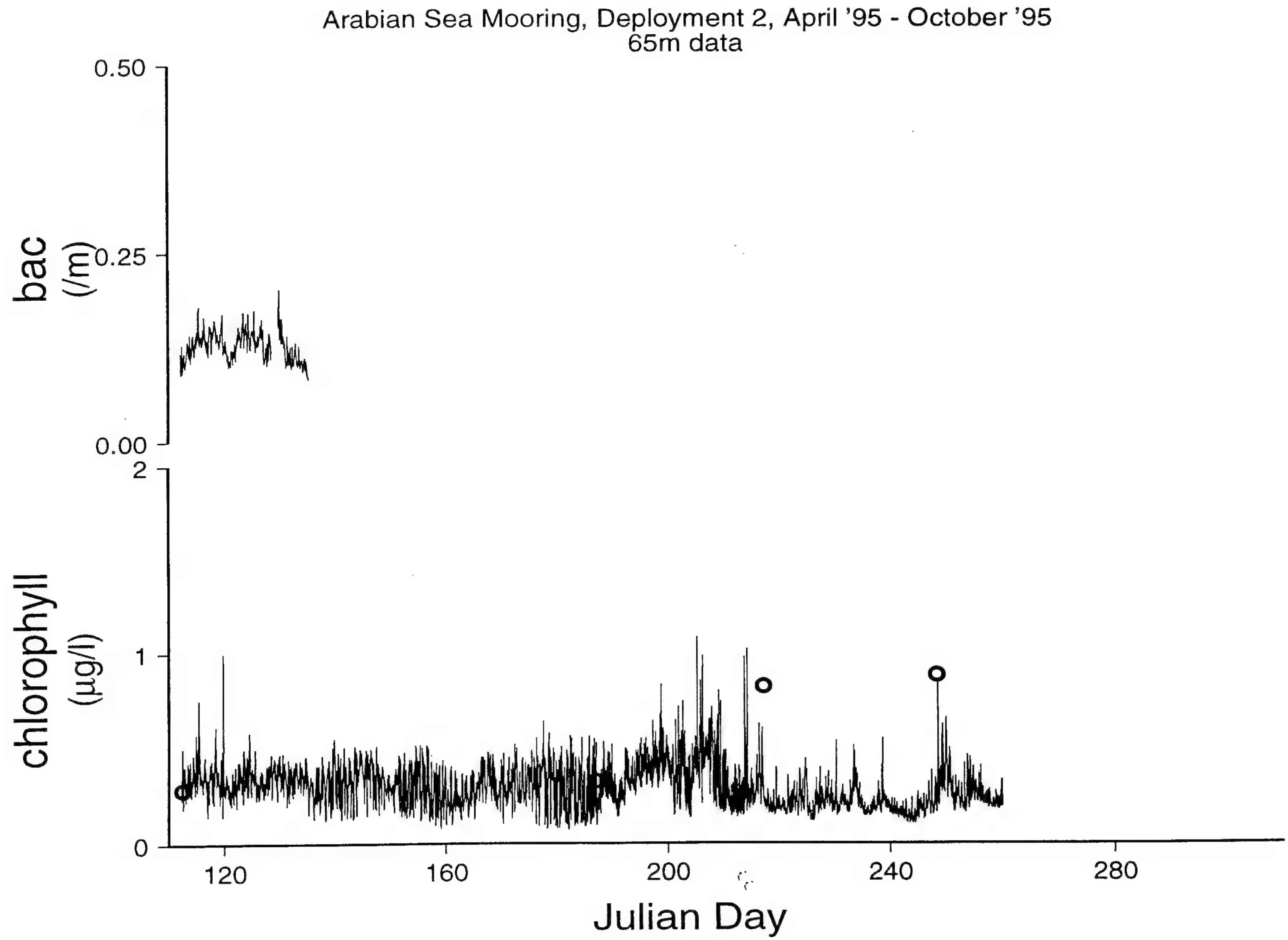
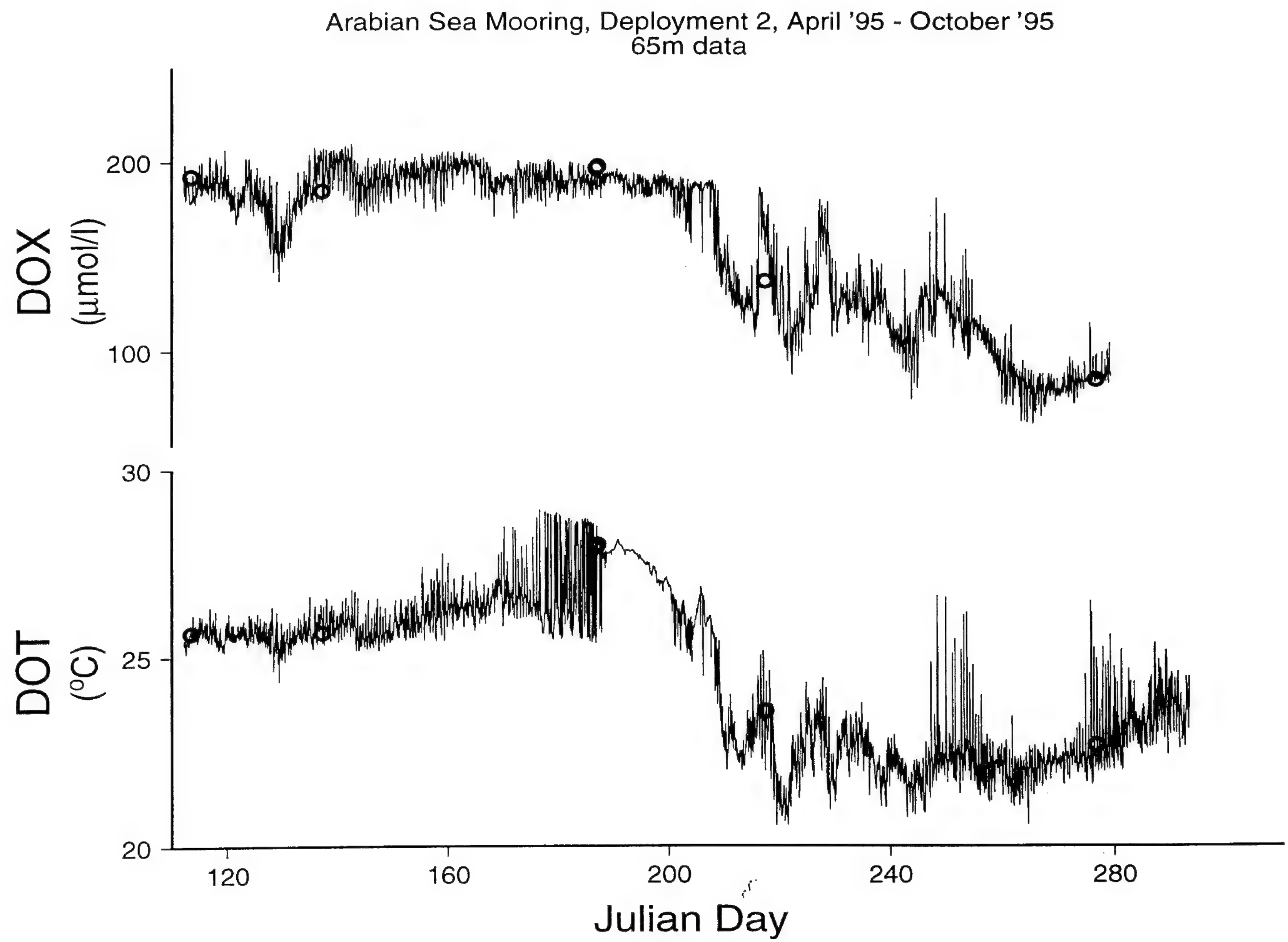

Arabian Sea Mooring, Deployment 2, April '95 - October '95
65m data
bac
(/m)
0.50
0.25
0.00
chlorophyll
(µg/l)
2
1
0
120
160
200
240
280
Julian Day

Fig.9



Arabian Sea Mooring, Deployment 2, April '95 - October '95
65m data
DOX
(μmol/l)
200
100
DOT
(°C)
30
25
20
120
160
200
240
280
Julian Day

Fig.10

Arabian Sea Mooring, Deployment 2, April, '95 - October, '95

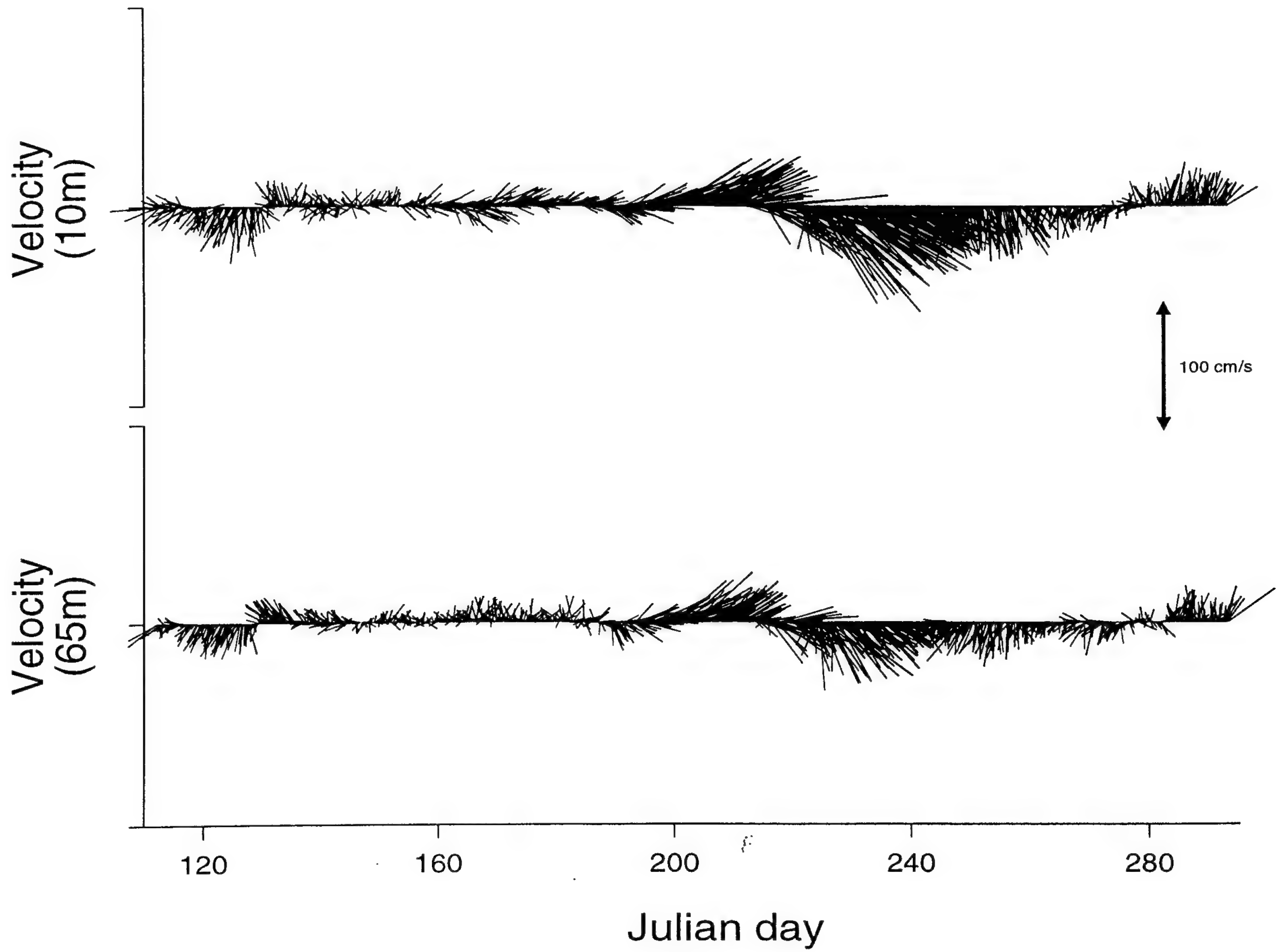


Fig.11

Appendix A: Calibration of the moored stimulated fluorescence data and evaluation of beam transmissometer data

A0: Introduction

Fouling was to be expected for the Arabian Sea mooring, and it occurred to a different degree depending on the sensor and its position (depth) on the mooring. Fluorometers and transmissometers were the most susceptible and the raw data had to be examined very carefully.

A1: Fluorometer Calibration Equations

On the cruise to deploy the mooring (TN046, April, 1995), we were able to collect a few chlorophyll samples to compare with the moored fluorometers. The chlorophyll analyses done on the cruise were a factor of 2-3 times lower than the laboratory calibration, completed a few months prior to the cruise. Since the lab calibration produced chlorophyll values much higher than the historical data from the Arabian Sea, we came to the conclusion that it was in error. Repeated checking of the laboratory calibration. however, failed to reveal the problem.

Since there were few calibration points for the fluorometer at the mooring site on subsequent cruises, and before it was suspected of being fouled, we settled on an alternative method used here and in the Deployment_1 Data Report (Ho *et al*,1996). We calibrated the fluorometer used on the CTD in terms of chlorophyll a, and used this to compare with the moored fluorescence values. In this way, we were able to re-cast the moored fluorescence data in terms of chlorophyll a, and also determine where in the record the fluorometers became fouled.

During Cruise TN049, JGOFS (Process Cruise 4) and Cruise TN050 (Process Cruise 5) extensive bottle samples were collected for chlorophyll analysis using Turner Designs fluorometer which had been calibrated with pure chlorophyll a (R.R. Bidigare, personal communication). Many of these samples were collected from CTD casts, which also used a fluorometer from SeaTech, and which was set at the same scale as the moored SeaTech fluorometer. Therefore chlorophyll values and the CTD fluorometer voltage readings supplied the best information to calibrate the moored fluorometers.

All chlorophyll data collected from CTD casts were identified, and the corresponding fluorometer reading from the same depth were extracted from the CTD files.

Fig. A1 shows all the data points. Linear regression produced the calibration equation:

$$\text{chl} = 0.4404 \cdot \text{Volt} - 0.108$$

,A 2: CTD Fluorescence Data

Before the fluorometer data were processed through calibration equation, they were de-spiked. There were two kinds: individual spikes and continuous spikes. Individual spikes can be deleted and replaced by previous data without changing the characteristic of the original data set. The continuous spike can not be deleted and replaced as easily. When the continuous spikes last only a few records, it may be replaced by previous good data without changing original data too much. If the continuous spike last over many records, the replacing with 'good data' may not be a good practice. Judging by Figs. A2 and A3, and detailed plots, it was determined that, for 10m, data after Day 200, there were too many long continuous spikes to make 'de-spiking' meaningful. For 65m, 'de-spiking' was stopped before Day 260.

The above calibration equations were then applied to de-spiked fluorometer data, chlorophyll values were calculated as shown on Figs. A4 and A5. Chlorophyll bottle data used for calibration and some CTD data at the mooring site were plotted with mooring data. Some of the bottle data might be as far as 100km from the mooring site. Since, in general, weather conditions and chemical properties were the same in the area of Arabian Sea, it is believed that these data could still be a very useful reference to determine whether mooring data were in a reasonable range.

For 10m, two important data points match exactly with mooring data. On Day 112, bottle data was collected at the mooring site. On day 187, it was independently calibrated and calculated from CTD data at the mooring site. These two data points ensure that mooring data between Day 112 and Day 187 were accurate. Data after Day 187 indicate that fouling was becoming serious. Conservatively we disregard all data after Day 187.

For 65m, bottle data at Day109 and CTD data at day 187 matched with mooring data again. Bottle data at Day 217 and Day 248, although 100km and 60km away from mooring site, showed values close to mooring data. The data did not show an abrupt change until Day 260. Data after Day 260 were flagged -9999 because of to fouling.

A3: Transmissometer Data

At 10 m, there was only about 60 days of 'clean' data. Unfortunately there were no CTD data available in this period. On Day 187,the CTD transmissometer showed a value of 0.132 m^{-1} for bac. At the same time the chlorophyll value was 0.214 μg/l and this was an average value of chlorophyll for time between Day 112 and Day 187. It would be reasonable to assume bac also had a average value of 0.132 m^{-1}. To be conservative, this value was assumed to be the highest bac value in this period. Accordingly, bac data between Day 120 and Day 160 were accurate (Fig. A4). All other data were flagged -9999.

At 65 m, the fouling problem was less serious. However, the transmissometer was unstable and measured unreasonably high bac. On Day 187, CTD chlorophyll value was at the level of average chlorophyll values of all time, but the same bac value was lower than any moored bac value, except those before Day 135.(Fig. A5). Data before Day 135 are presented for reference, the rest were flagged -9999.

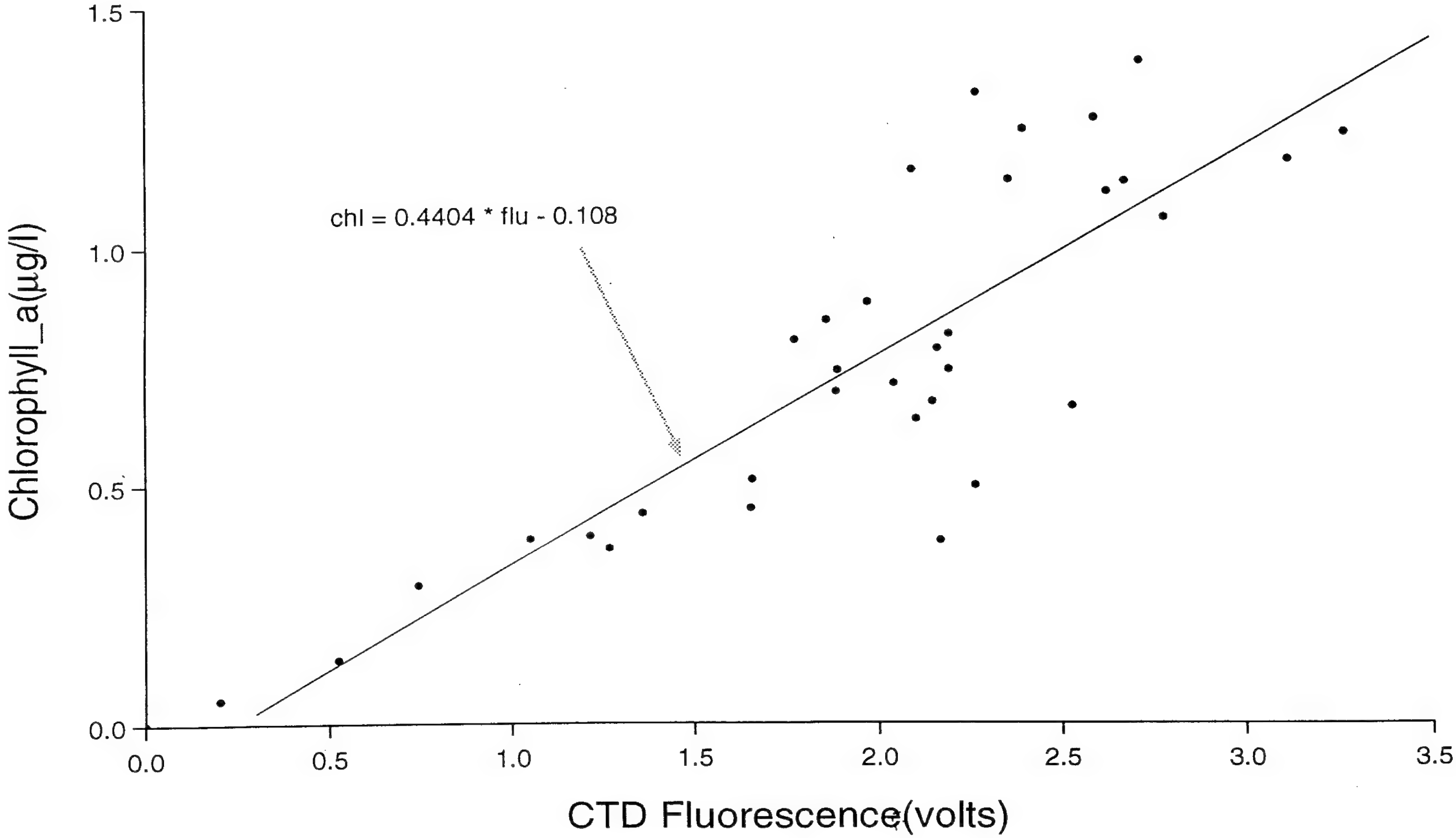
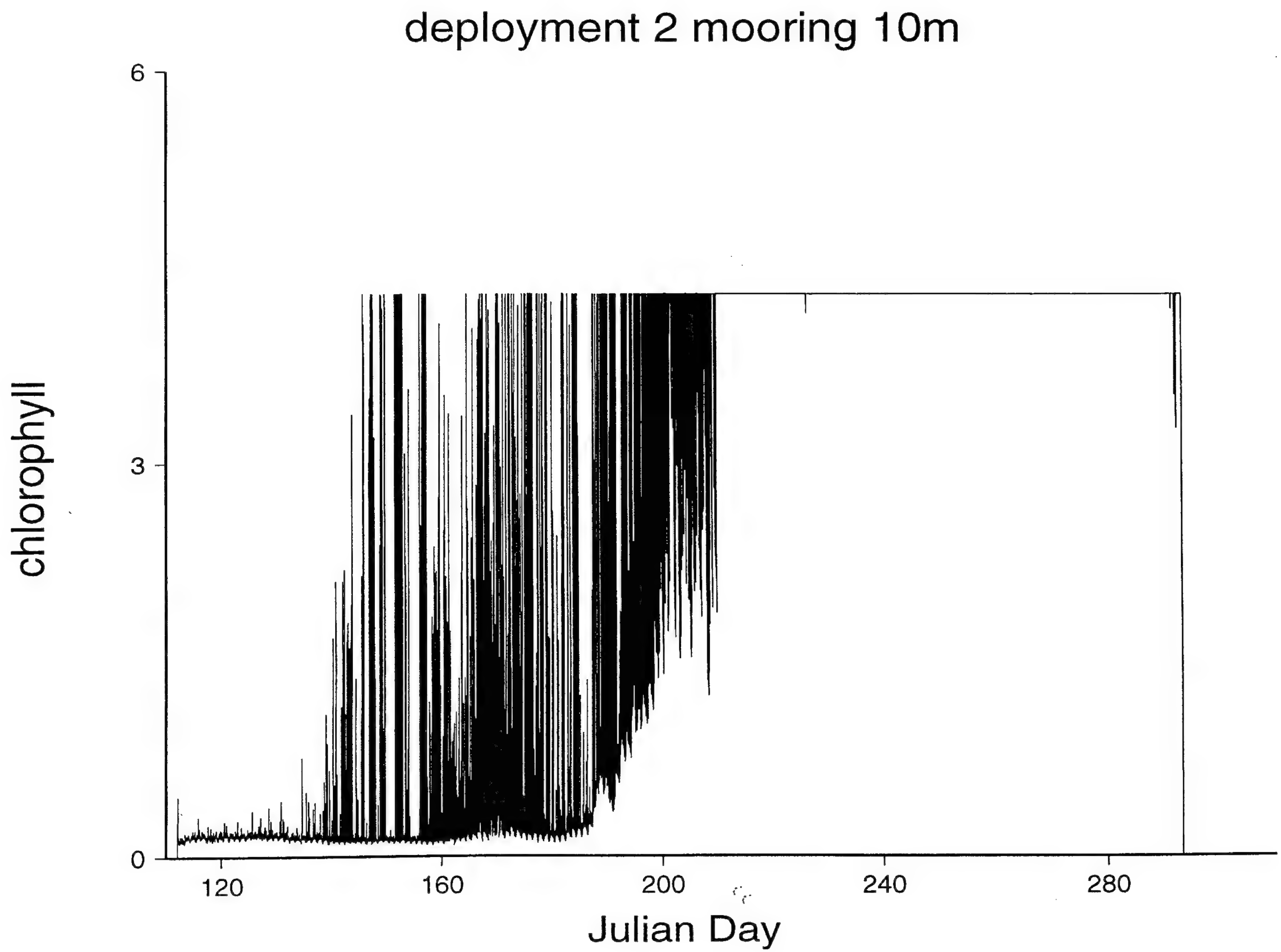
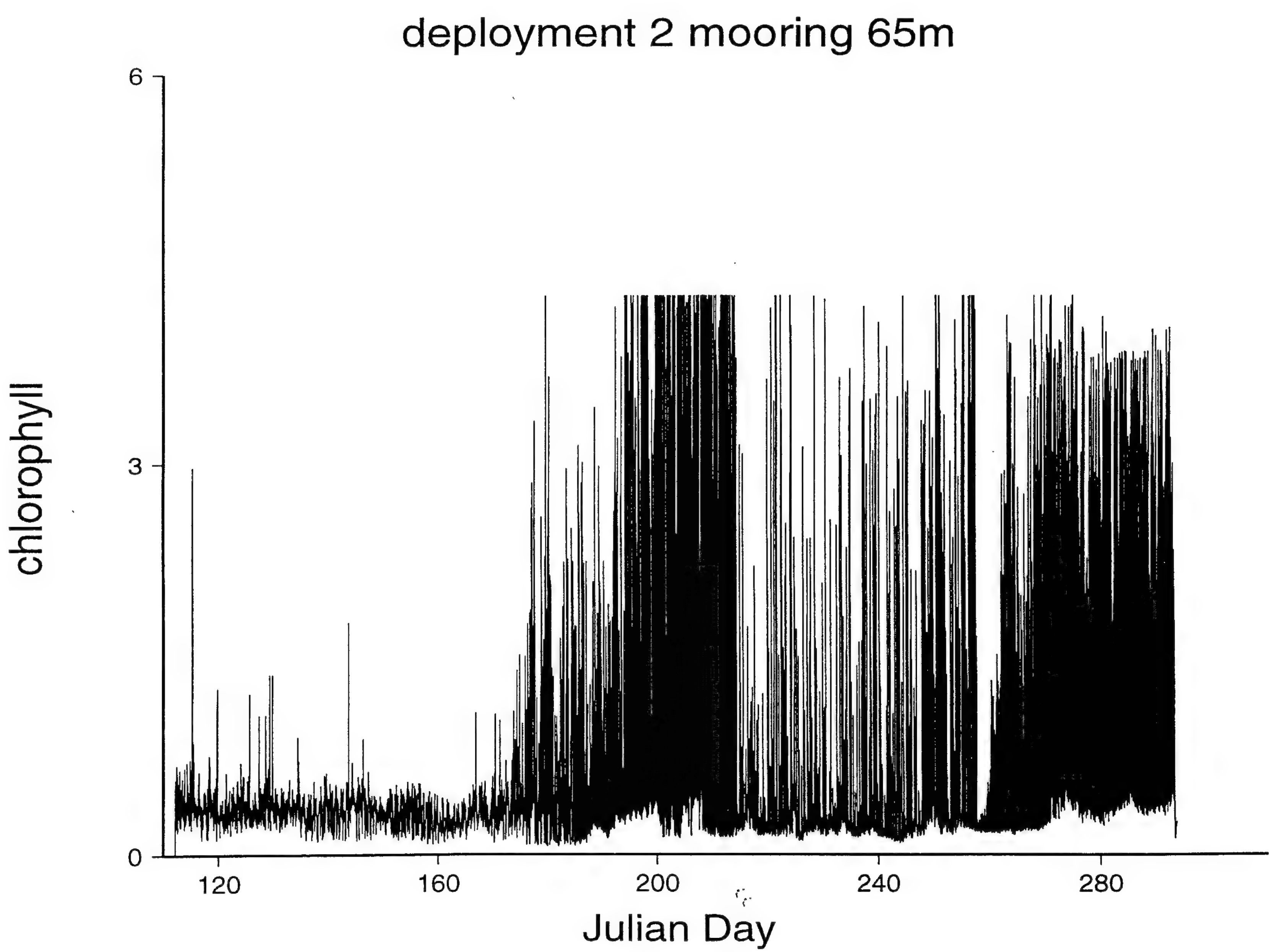
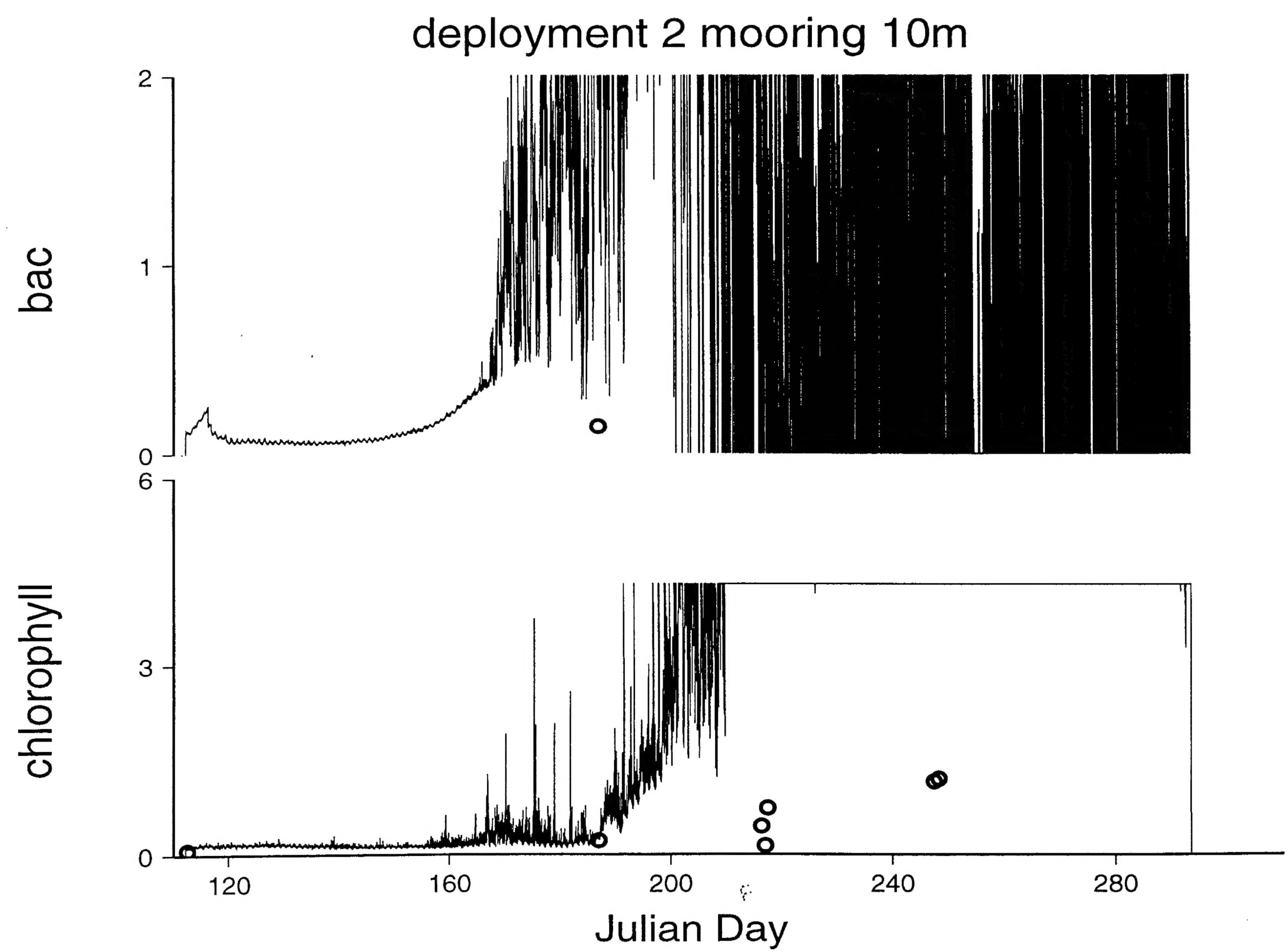

chl = 0.4404 * flu - 0.108
Chlorophyll_a(µg/l)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
CTD Fluorescence(volts)

Fig. A1


deployment 2 mooring 10m
chlorophyll
6
3
0
120
160
200
240
280
Julian Day
Fig.A2


deployment 2 mooring 65m
chlorophyll
6
3
0
120
160
200
240
280
Julian Day
Fig.A3


deployment 2 mooring 10m
bac
2
1
0
chlorophyll
6
3
0
120
160
200
240
280
Julian Day
Fig.A4

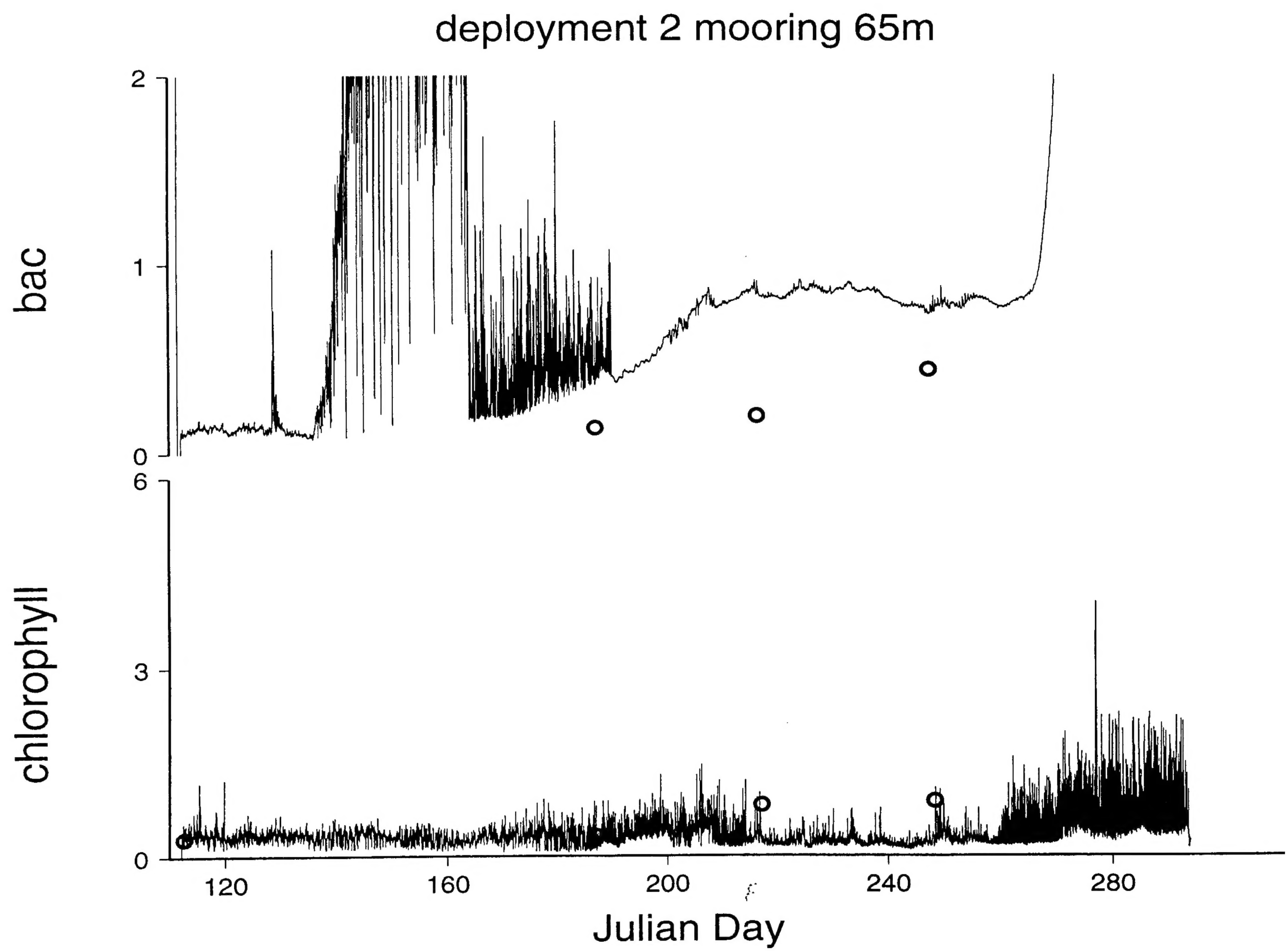

deployment 2 mooring 65m
bac
2
1
0
chlorophyll
6
3
0
120
160
200
240
280
Julian Day

Fig.A5

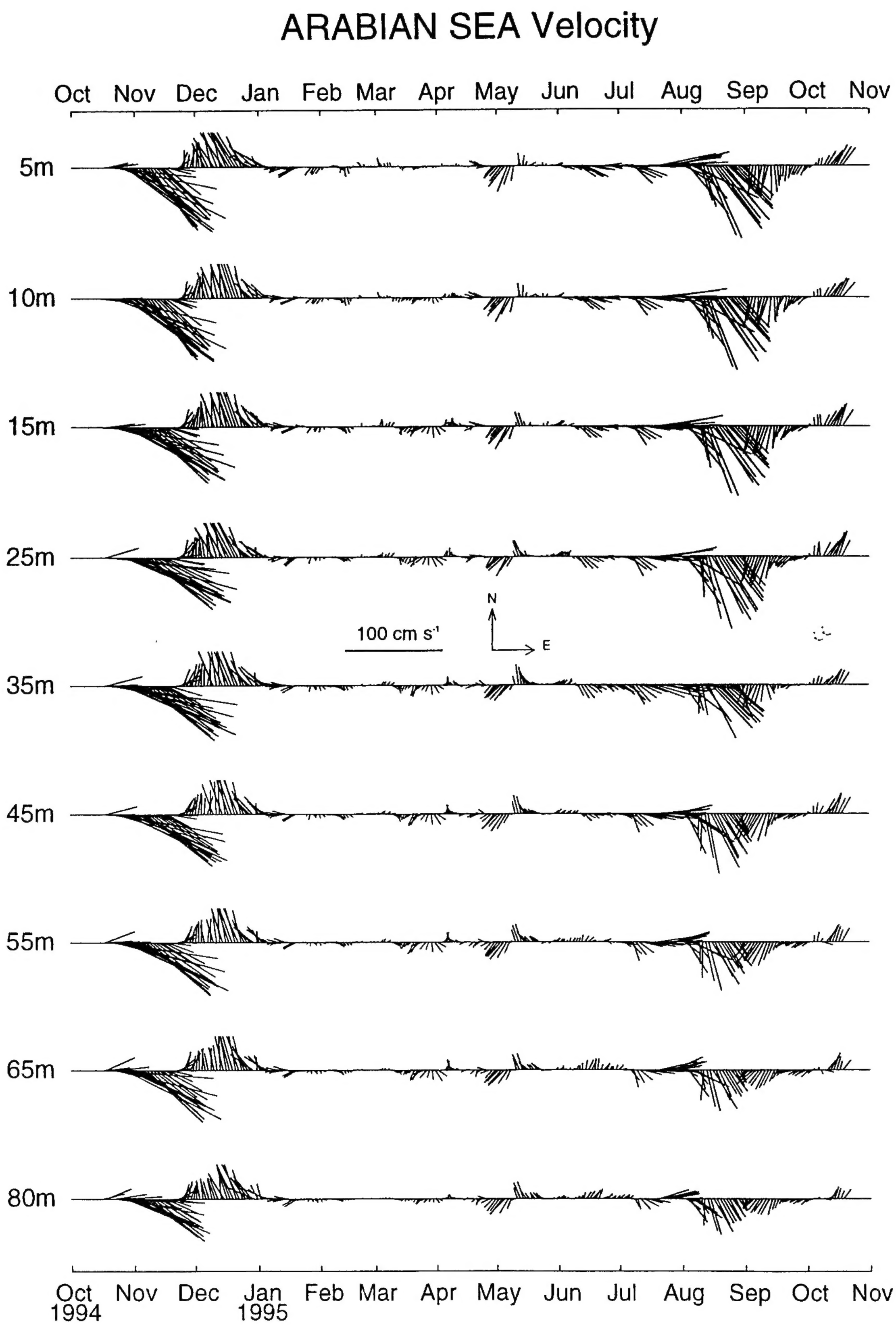

ARABIAN SEA Velocity
Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov
5m
10m
15m
25m
35m
45m
55m
65m
80m
100 cm s⁻¹
N
E
Oct 1994
Nov
Dec
Jan 1995
Feb Mar Apr May Jun Jul Aug Sep Oct Nov

Fig.B1

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13. ABSTRACT *(Maximum 200 words)*

Multi-variable moored system were used to collect physical and bio-optical data over a six month period in the Arabian Sea (15 30'N/61 30'E) from Apr 22,'95 to Oct.20,'95.We present data from MVMS'positioned at 10 and 65 m depth. Calibration and validation issues are considered in the presentation of data.

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